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TECHNICAL NOTE

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ANALYTICAL AND PRELIMINARY SIMULATION STUDY OF A PILOT'S ABILITY TO CONTROL THE TERMINAL PHASE OF A RENDEZVOUS WITH SIMPLE OPTICAL DEVICES AND A TIMER

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SUMMARY

One method of controlling the terminal phase of a space rendezvous between two vehicles is first to correct the flight path of the controlled vehicle so that a constant line of sight is established between the vehicles. This correction is accomplished by thrusting normal to the sight line in a direction to arrest the angular motion of this line. Once this collision course has been established, the second step is to control the closure rate for a safe approach along the line of sight. Adequate control of this maneuver requires range and closure-rate information. A combined analytical and preliminary simulation study was conducted to determine the ability of a human pilot to control the rendezvous by this method using visual sightings made during the initial collision-course control to obtain the range and closure rate.

The analytical phase of the study reviewed the geometric relations between the vehicles and formed the basis for techniques to transform the angular sightings into range and closure rate. A preliminary simulation was then made to investigate the accuracy of these techniques. The simulation consisted of an analog computer, an oscilloscope to represent the view a pilot would have with a stabilized sight, and a timer.

Results indicate that pilots, using an optical sight and a timer, can successfully arrest the angular motion of the line of sight between two rendezvous vehicles and obtain relative range and closure rate with sufficient accuracy to perform the final braking maneuver successfully.

INTRODUCTION

The abilities of a human pilot can be utilized in future space control systems to simplify equipment requirements and thus add to system reliability. One type of mission for which the capabilities of a human pilot can be used to an advantage is the terminal phase of a space rendezvous between two vehicles.

Previous studies made of rendezvous show that a human pilot can control the terminal or closing phase of such a mission even with adverse initial conditions if he has adequate information available. Reference 1 reports results of a simulator study in six degrees of freedom wherein the pilot was furnished the required data on dialed instruments. References 2 and 3 are examples of rendezvous simulation studies conducted with the vehicles in coplanar orbits. In references 1 and 2 the assumption was made that range and closure-rate data would be measured by onboard equipment. In reference 3 the simulation was confined for the most part to less than a half-mile range so that the pilot could judge approach distance by the apparent increase in size of the simulated target. In the present study the initial range is sufficiently long so that the pilot has no appreciation of the size of the target and observes it simply as a point of light. Techniques are developed to permit the pilot by means of optical sightings taken prior to and during a thrusting period to obtain information on range and closure rate necessary for control of the rendezvous maneuver. This technique could eliminate the need for onboard sensing equipment such as tracking radar. In addition, the ability of the human pilot to scan large areas is an advantage over some sensing systems with a limited field of view.

The method of control of the terminal phase of a rendezvous used herein requires that the pilot first establish a constant-line-of-sight approach to the target vehicle by arresting angular motions of the sight line, and then control the closure rate of his vehicle along the constant line of sight with a schedule for braking to effect safe contact. Both angular control with transverse rockets and braking with longitudinal rockets would be performed by using thrust accelerations of known levels.

An optical sight would permit a pilot to detect and measure visually the angular motion of the line of sight relative to a fixed reference system, such as a star background or stable platform, for corrections. In order to control the closure rate, however, the pilot must have range and closure-rate information.

In the present paper various techniques for using optical information and a timer to obtain the required relative range and closure rate, while the required constant-line-of-sight approach is established, have been explored analytically. Results of a preliminary simulation study that was conducted to determine the pilot's ability to control the terminal rendezvous phase utilizing these techniques are included.

SYMBOLS

L1697 The British system of units is used in this paper. For conversion to metric units, the following relations apply:

$$1 \text{ foot} = 0.3048 \text{ meter}$$

$$1 \text{ statute mile} = 5{,}280 \text{ feet}$$

a	acceleration, ft/sec^2
R	range between vehicles, statute miles or ft
σ	line-of-sight angles in XY motion plane, radian
τ	thrusting time, sec
X,Y	coordinate axes fixed in inertial space with origin in target vehicle
x,y	coordinates along X- and Y-axes
t	time, sec

Subscripts:

o	initial
1,2,3	sequence
t	time at which value occurs
N	denotes component normal to line of sight to target
R	denotes radial component along line of sight to target

calc calculated

A actual (from analog records)

A dot over a quantity denotes differentiation with respect to time.

ANALYSIS OF TECHNIQUES

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A two-dimensional analysis was used in the present study to develop simple expressions for relative range and closure rate between two rendezvous vehicles based upon known parameters and those which can be measured by a pilot. The axis system used in the study is shown in figure 1. The origin of the reference frame is established in the target vehicle with the X-axis initially alined with the line of sight to the ferry vehicle. The Y-axis is parallel with the initial direction of the component of velocity of the ferry normal to the line of sight. In practice, this situation could be applied to a three-dimensional case by confining all control forces to this plane of motion.

The only force assumed to influence the motion between the two vehicles is rocket motor thrust. The analysis of reference 1 has shown that the gravity-gradient effects on neighboring space bodies are negligible. When the gravity-difference terms are omitted, the equations of relative motion between the two vehicles, expressed in polar coordinates, are

$$\ddot{R} - R\dot{\sigma}^2 = a_R \tag{1}$$

and

$$R\ddot{\sigma} + 2\dot{R}\dot{\sigma} = a_N \tag{2}$$

Based on these equations of relative motion, three techniques were developed for determining the range and closure rate existing between the two rendezvous vehicles. One technique required measuring two angular increments traversed by the moving line of sight while coasting, and a third angular increment while a known level of acceleration is applied to arrest the line-of-sight motion. A second technique required measuring the two angles while coasting but not the third angle while thrusting. A third technique required the same measurements as the first technique to be used as inputs to a matrix solution and produced several progressive solutions, but dictated the use of additional equipment for rapid, continuous computing.

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The first technique developed to determine range requires that the pilot observe the motion of the target with respect to the star background, as depicted in figure 2. For simplicity the target is shown creating the angular motion of the sight line. A grid in the sighting instrument is then alined with this target motion to allow measurements of angles traversed as a function of time. Next the control thrust of the ferry vehicle is alined normal to the initial line of sight to the target to oppose the line-of-sight motion. The pilot then applies a known level of thrust acceleration long enough to arrest the angular motion of the line of sight, bringing the target to rest with respect to the star background. The thrusting time τ required to arrest the angular motion and the angle σ are measured. This procedure of arresting the line-of-sight rate at the earliest opportunity tends to minimize fuel usage, as shown in reference 1. The parameters obtained during this initial phase of the rendezvous maneuver are depicted in figure 1. With no applied thrust the range at any point along the trajectory may be expressed as

$$R = \frac{\dot{y}_o t}{\sin \sigma} \tag{3}$$

Consequently, when σ is small

$$R_1 = \frac{\dot{y}_o t_1}{\sigma_1} \tag{4}$$

$$R_2 = \frac{\dot{y}_o t_2}{\sigma_2} \tag{5}$$

Dividing equation (4) by equation (5) gives

$$R_1 = R_2 \frac{\sigma_2 t_1}{\sigma_1 t_2} \tag{6}$$

or a functional relationship between ranges based upon angles traversed by the line of sight, and the respective times required to traverse the angles. For clarity, consider a new reference frame with the X-axis alined along R_2 as shown in figure 3. If thrust is initiated normal to the range vector R_2 and opposing $\dot{y}_o$ at a reference time $t = 0$, then

$$\dot{y} = -a\tau + \dot{y}_o \tag{7}$$

Integrating this expression gives

$$y = -\frac{a\tau^2}{2} + \dot{y}_o\tau \tag{8}$$

If adequate thrust is maintained until the angular motion of the line of sight is arrested, the angle σ will be quite small and

$$\dot{y} = \dot{R}\sigma \tag{9}$$

(Satisfying equation (9) assures that the remaining resultant relative velocity is along the range vector R_3.) Substituting equation (9) into equation (7) yields

$$\dot{y}_o = a\tau + \dot{R}\sigma \tag{10}$$

Substituting equation (10) into equation (8) gives the distance y traveled while thrusting as

$$y = \frac{a\tau^2}{2} + \dot{R}\sigma\tau \tag{11}$$

But

$$R_3\sigma = y \tag{12}$$

therefore

$$R_3 = \frac{a\tau^2}{2\sigma} + \dot{R}\tau \tag{13}$$

The range R_3 can also be expressed as

$$R_3 = R_2 + \dot{R}\tau \tag{14}$$

Combining equations (13) and (14) gives

$$R_2 = \frac{a\tau^2}{2\sigma} \tag{15}$$

which is the relative range at the initiation of the thrusting maneuver for establishing a collision course. Substituting the value of the range determined from equation (15) into equation (6) affords a solution for the range R_1. The closure rate can be determined from the range and time differentials

$$\dot{R} = \frac{R_2 - R_1}{t_2 - t_1} \tag{16}$$

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The second technique developed is based upon the pilot's making timed angular measurements of σ during a period in which no thrust is applied. The pilot would then measure the time τ while thrusting with a known level of acceleration to arrest the angular motion. This method differs from the previous one in that measurement of the angular travel during the thrusting period is not required. Equation (2), the exact expression for normal acceleration, can be expressed as

$$\frac{1}{R}\frac{d}{dt}\left(R^2\dot{\sigma}\right) = a_N \tag{17}$$

and with no applied thrust $(a_N = 0)$

$$\frac{1}{R}\frac{d}{dt}\left(R^2\dot{\sigma}\right) = 0 \tag{18}$$

Therefore,

$$R^2\dot{\sigma} = \text{Constant} = R_o\dot{y}_o \tag{19}$$

Substituting the relationship expressed in equation (4) that

$$\dot{y}_o = \frac{R\sigma}{t} \tag{20}$$

into equation (19) yields

$$R_o = \frac{R\dot{\sigma}t}{\sigma} \tag{21}$$

If thrust is initiated at time t and maintained until the angular motion of the line of sight is arrested, then

$$R\dot{\sigma} \approx a\tau \tag{22}$$

Substituting equation (22) into equation (21) gives

$$R_o = \frac{a\tau t}{\sigma} \tag{23}$$

The zero reference for σ is purely arbitrary, however, and equation (23) can be expressed as

$$R_n = \frac{a\tau t_n}{\sigma_n} \qquad (n = 0, 1, 2, 3, \ldots) \tag{24}$$

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where n denotes the zero reference for t and σ. A subsequent solution of the closure rate thus becomes

$$\dot{R} = \frac{R_{(n+m)} - R_n}{t_n - t_{(n+m)}} \qquad (m = 1, 2, 3, \ldots) \tag{25}$$

The third technique developed in the study differs from the aforementioned ones in that several solutions for range and closure rate are afforded during the reduction of the normal velocity component to zero in steps. From figure 3

$$\tan \sigma = \frac{\dot{y}_o t - \frac{a\tau^2}{2}}{x_o - \dot{x}_o t} \tag{26}$$

or for small angles

$$x_o\sigma - \dot{x}_o t\sigma - \dot{y}_o t = -\frac{a\tau^2}{2} \tag{27}$$

With no applied thrust

$$x_o\sigma_1 - \dot{x}_o t_1\sigma_1 - \dot{y}_o t_1 = 0 \tag{28}$$

$$x_o\sigma_2 - \dot{x}_o t_2\sigma_2 - \dot{y}_o t_2 = 0 \tag{29}$$

and for a period of thrusting through time τ

$$x_o\sigma_3 - \dot{x}_o t_3\sigma_3 - \dot{y}_o t_3 = -\frac{a\tau^2}{2} \tag{30}$$

where σ_1, σ_2, and σ_3 are angles traversed by the line of sight from a zero reference, and t_1, t_2, and t_3 are the respective times required to traverse the angles. Thus three simultaneous equations evolve in the unknown quantities x_o, $\dot{x}_o$, and $\dot{y}_o$. From figure 3

$$x_o = R_2$$

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and when σ is small

$$\dot{x}_o \approx \dot{R}$$

therefore, the solutions provide the quantities required for the rendezvous maneuver. A lightweight onboard computer or a radio link to a ground-based computer would be required to solve the simultaneous equations (28), (29), and (30) with the use of the pilot's inputs of the measured angles and times.

CLOSURE-RATE CONTROL

The initial part of the terminal control described in the previous section furnishes the required information for computing range and closure rate while a collision course is established. Then the second part, that of scheduling braking thrust along the stationary line of sight to the target, can be effected until the vehicles are close enough to permit other visual cues for control. An example of one technique developed in the present study is shown in figure 4 which is a summary plot of figures 1 and 3. This technique, developed as equations (15) and (16), is the first one described in the previous section entitled "Analysis of Techniques." Figure 4 presents the sequential operations the pilot would follow using this technique to determine range and closure rate. This information would determine the length of time that a prescribed thrust level must be applied to get to zero closing velocity and would allow the pilot to follow some prescribed braking schedule such as that shown in figure 5.

If the pilot wishes to effect a rendezvous in the minimum time, he could delay the braking thrust until the acceleration capability of his vehicle is approached. This maneuver is dictated by the upper acceleration boundary of figure 5, unique for each acceleration level. However, this minimum-time method of slowing down increases the task of making corrections to residual angular motions and increases misalinement thrust and damping effects. The easier braking schedule would fall somewhere below the schedule shown in figure 5, with time intervals between thrusting to make corrections to line-of-sight deviations and to anticipate control effects. This type of braking was found to be more desirable in the investigation conducted in reference 1, insuring safe closure rates at lower ranges. In any event, the fuel use would be the same for reducing a specific closure rate, and the pilot is only required to time the sum of the separate thrusting periods. If a braking schedule is adhered to, the closure rate would be reduced to a safe value as the relative range decreases so that the pilot can rely on such visual cues as the apparent increase in size of the target as he approaches it.

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DESCRIPTION OF SIMULATION STUDY

Simulations of the terminal phase of a pilot-controlled rendezvous with the use of simple optical equipment and a timer were carried out to support the analytical techniques derived in the study. A picture of the simulation equipment is shown in figure 6. An analog computer solved the space and body equations of motion of the two vehicles involved in the rendezvous maneuver. Outputs from the analog computer drive a moving dot across an oscilloscope grid to simulate the optical viewer and angular grid shown in figure 2. The simulator pilot used a stop watch to time the dot as it moved across the grid and noted the distance traversed during each interval. These measured times and angles were inputs to the analytical expressions for range and closure rate. The grid was calibrated to show the angular change in the line of sight between the vehicles and could be read by the pilot to within 1 milliradian.

Previous attitude-control work carried out in reference 1 proved that reorienting the ferry-vehicle axes presented no problem; therefore, in the present preliminary visual study the analog computer was programed the same as in a concurrent automatic rendezvous study and performed the reorientation function. The task of the pilot consisted of reading and timing the angular motion of the target dot on the oscilloscope grid and applying a known thrust level with the vehicle normal to the line of sight to arrest the motion. He could then actuate a switch that would automatically aline the thrust axis of the vehicle with the line of sight. The alinement and thrust switches were on the analog console and can be seen in figure 6. During the 23 seconds that was required for the computer to reorient the vehicle 90° to aline the single thrust vector along the line of sight for braking, the pilot could compute range and closure rate by means of the simple mathematical techniques with the use of a slide rule. Knowing the approximate range and closing speed, the pilot could initiate the desired velocity increments by actuating the thrust switch to reduce the closure speeds to safe levels as the two vehicles became closer. In the actual case, having to reorient the vehicle attitude to direct the thrust of a single rocket would require additional work for the pilot. Multiple rockets might be used advantageously to eliminate the need for large vehicle rotations once the rendezvous maneuver had begun; thus, the pilot would be free during coasting intervals to perform monitoring and other duties.

RESULTS AND DISCUSSION

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The analytical portion of this study was concerned with the development of simple expressions for determining range and closure-rate information with sufficient accuracy to enable a pilot to effect a successful space rendezvous. The results obtained by an application of the various techniques in a simulation study on an analog computer are compared with the actual values of range and closure rate.

The results of ten runs obtained by a pilot applying the technique of equations (15) and (16) are presented in table I for various conditions existing at the beginning of the terminal rendezvous phase. The initial conditions are R_o, $\dot{R}_o$, and $(R\dot{\sigma})_o$. Table I shows calculated and actual recorded values of range and range rate identified at the end of the time that elapsed while the pilot secured his optical information. For these runs it can be seen that a typical measuring time was about 1 minute for this technique. This measuring time encompassed the task of measuring and timing the accrued line-of-sight angle over two 10-milliradian coasting intervals and one control interval while the angular rate was brought to zero. The error in range and closure rate is also tabulated. The standard deviation for values of range calculated by this technique is 0.65 mile, or 1.61 percent, and for values of closure rate it is 34 feet per second, or approximately 6 percent, where standard deviation is expressed as

$$\text{s.d.} = \frac{(y - \bar{y})^2}{N - 1}$$

where y is the calculated value at a point, $\bar{y}$ is the average, and N is the number of points. Figure 7 shows a time history of a typical trajectory for the data in table I. Also shown is a coasting period following the application of the technique for establishing range and closure rate that could be used for making calculations, and the braking schedule that was followed to effect a safe approach to within 1 mile and within a closure rate of 100 ft/sec to allow final docking with visual contact.

Typical values obtained with the technique of equations (24) and (25) are tabulated in table II. This technique is particularly well suited to a simple special-purpose electronic computer and required three 10-second intervals to determine the angle traversed during two coasting intervals and one thrusting interval. Thus, the measuring time was half that required for the previous technique, and accuracies were comparable. The standard deviation for values of range in table II is 0.8 mile, or 1.75 percent, and the more important calculation of closure rate was 34.2 ft/sec, or 4.78 percent of the average closure rate that actually existed. Figure 8 depicts a time history of a typical trajectory for the data in table II.

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The third technique investigated in the present study, although possibly producing more accurate values of range and closure rate, was too involved for a pilot to utilize quickly enough without the help of additional computing equipment. An onboard computer or radio link to a ground computer would simplify the pilot's task by accepting his optical measurements and in turn displaying range and closure rate continuously.

The overall results of this analytical and preliminary simulation study of simplified techniques for a space rendezvous obtained with a sighting instrument, stop watches, and a slide rule show that a pilot can control the terminal phase to within 1 mile and within a closure rate of 100 ft/sec. Further simulations in which the pilot completely controls attitudes and rates of the vehicle are required to fully prove the feasibility of these techniques.

CONCLUSIONS

A combined analytical and preliminary simulation study has been made to determine the ability of a human pilot to control the terminal phase of a space rendezvous by using optical measurements and simple computations. The conclusion was reached that a human pilot, using a simple optical sighting device, can determine the parameters necessary for computing the relative range and closure rate existing between his vehicle and another space vehicle while arresting the angular motion between the two vehicles, and can do so with sufficient accuracy to perform the final braking maneuver safely to a point where the rendezvous can be completed from direct visual cues.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Air Force Base, Va., August 1, 1961.

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TABLE I

COMPARISON OF ACTUAL AND COMPUTED VALUES OF RANGE AND CLOSURE RATE

OBTAINED BY PILOT USING FIRST TECHNIQUE

$\left[R_o = 264{,}000 \text{ ft}\right]$

Run number	$\dot{R}_o$, ft/sec	$(R\dot{\sigma})_o$, ft/sec	$R_{C,t}$, ft	$R_{A,t}$, ft	$\dot{R}_{C,t}$, ft/sec	$\dot{R}_{A,t}$, ft/sec	t, sec	$(R_A - R_C)_t$, ft	$(\dot{R}_A - \dot{R}_c)_t$, ft/sec
1	-400	200	246,000	241,200	-378	-404	57	-4,800	-26
2	-400	200	226,000	239,386	-353	-404	59	13,386	-51
3	-800	200	202,000	213,879	-784	-809	60	11,879	-25
4	-800	200	205,000	216,003	-800	-807	56	11,003	7
5	-997	200	211,000	207,769	-1,020	-1,006	54	-3,231	14
6	-997	200	204,000	211,580	-960	-1,006	50	7,580	-46
7	-997	100	172,000	182,470	-925	-1,000	79	10,470	-75
8	-997	300	212,000	224,389	-950	-1,010	38	12,389	-60
9	-997	400	226,000	232,043	-1,000	-1,012	31	6,043	-12
10	-500	300	230,000	239,069	-480	-505	50	9,069	-25

TABLE II

COMPARISON OF ACTUAL AND COMPUTED VALUES OF RANGE AND CLOSURE RATE

OBTAINED BY PILOT USING SECOND TECHNIQUE

$\left[R_o = 264{,}000 \text{ ft}\right]$

Run number	$\dot{R}_o$, ft/sec	$(R\dot{\sigma})_o$, ft/sec	$R_{C,o}$, ft	$R_{C,t=30}$, ft	$R_{A,t=30}$, ft	$\dot{R}_{C,t=30}$, ft/sec	$\dot{R}_{A,t=30}$, ft/sec	$(R_A - R_C)_{t=30}$, ft	$(\dot{R}_A - \dot{R}_C)_{t=30}$, ft/sec
1	-400	200	262,000	249,000	252,000	-433	-404	3,000	29
2	-600	200	263,000	243,000	246,000	-667	-605	3,000	62
3	-800	200	261,000	237,000	240,000	-800	-809	3,000	-9
4	-1,000	200	259,000	228,000	234,000	-1,031	-1,006	6,000	25
5	-1,000	300	266,000	235,000	234,000	-1,031	-1,010	-1,000	21
6	-500	300	259,000	244,000	249,000	-500	-505	5,000	-5

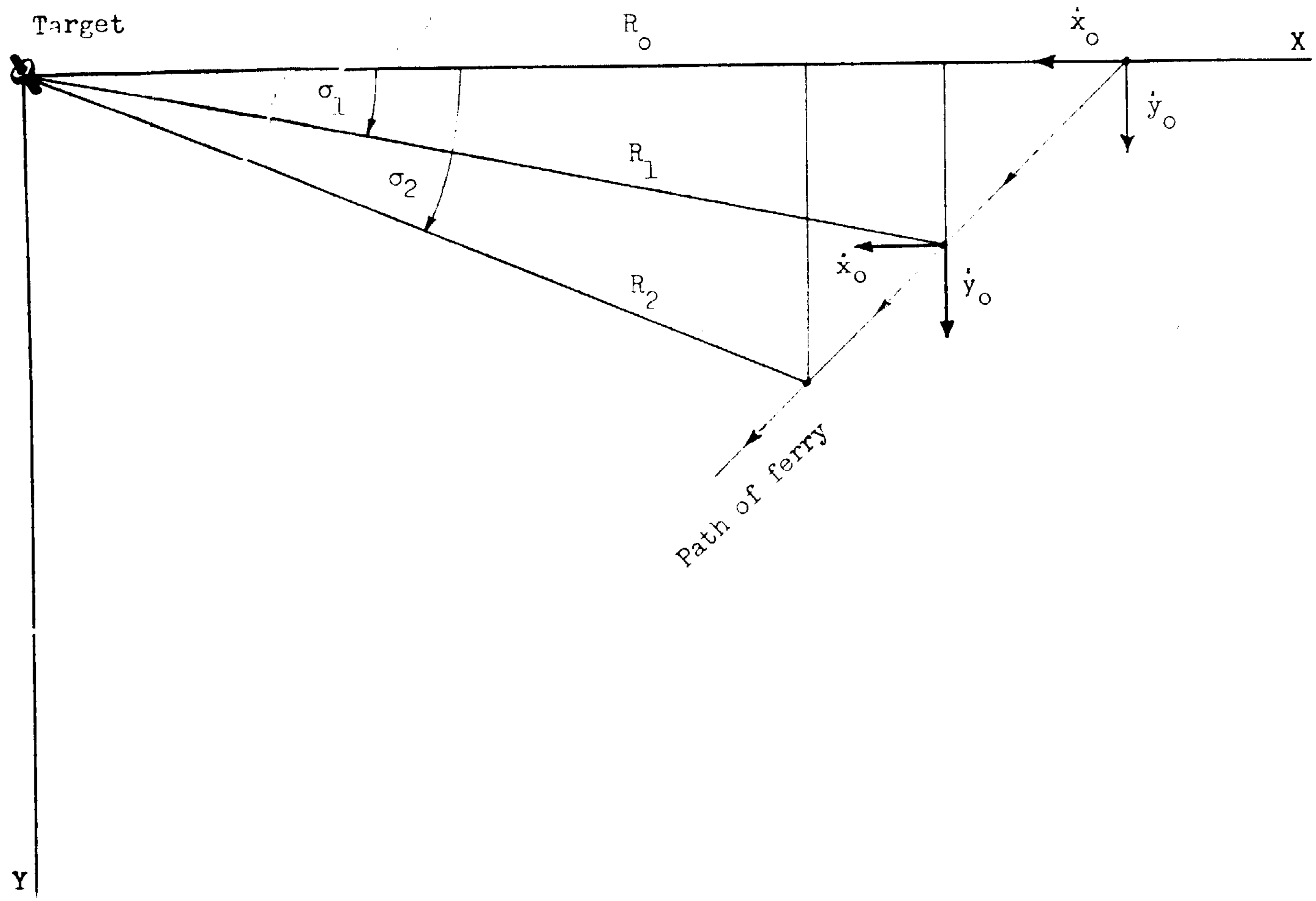

Figure 1.- Two-dimensional axis system defining relative motion between target and rendezvous vehicle.

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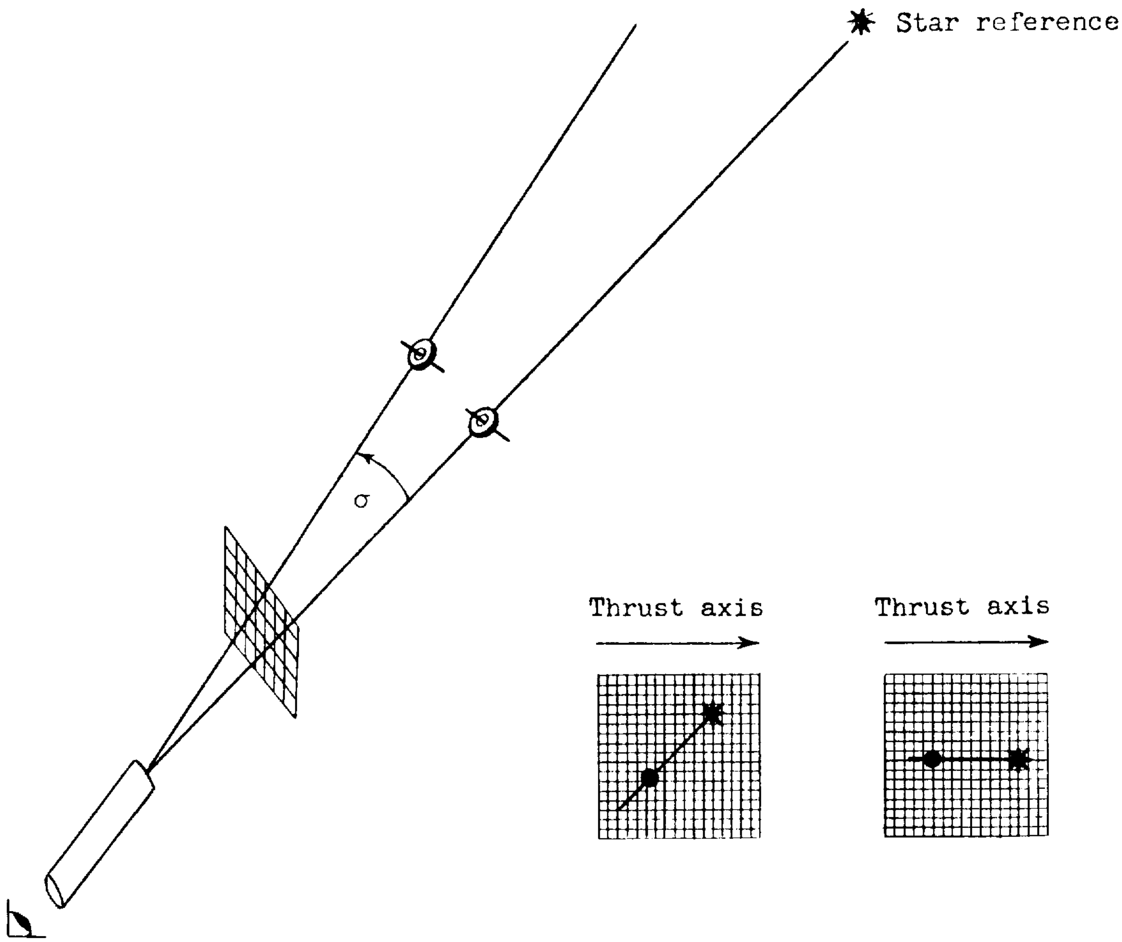

Figure 2.- Optical sighting instrument.

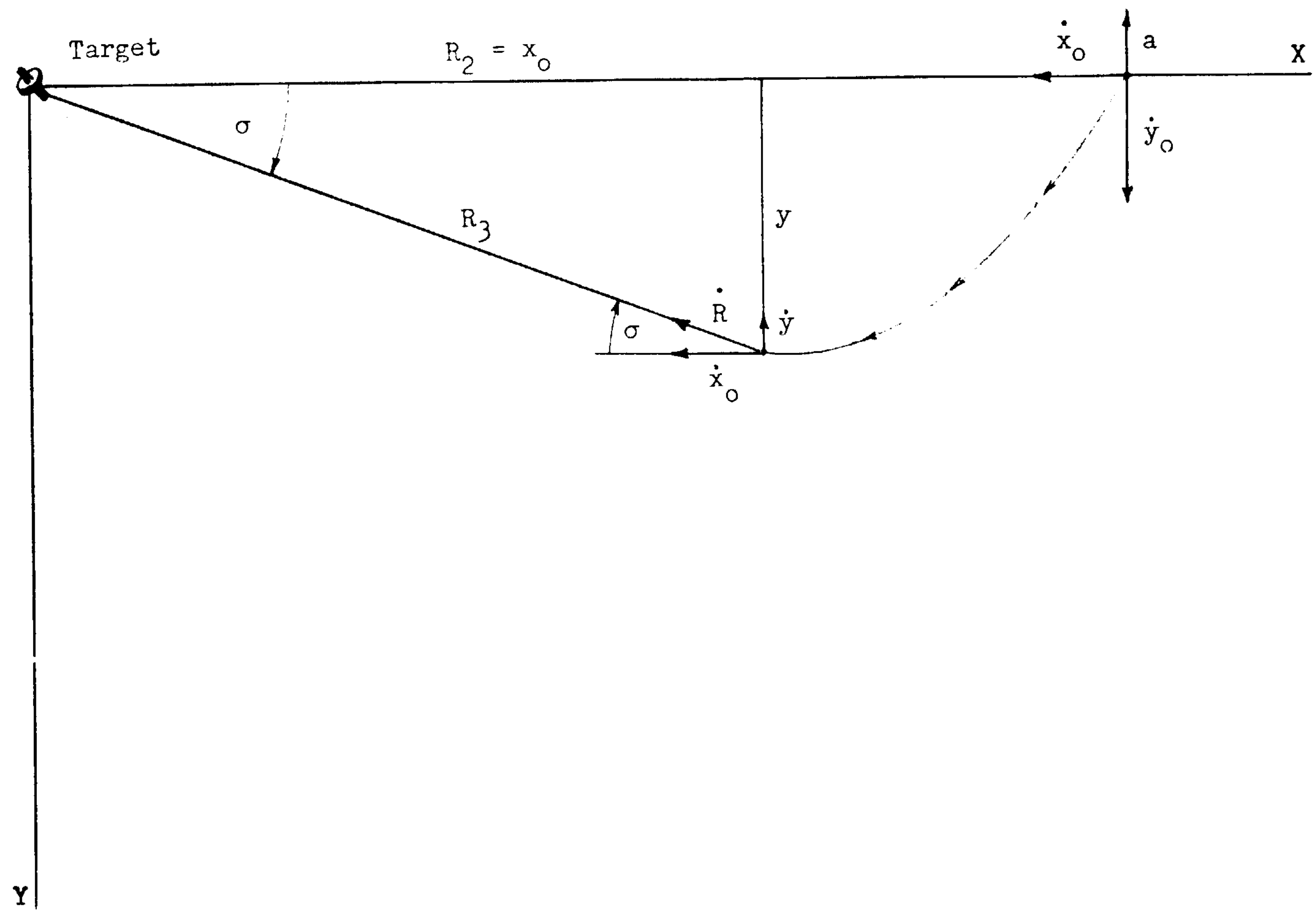

Figure 3.- Thrusting technique to arrest angular motion of line of sight.

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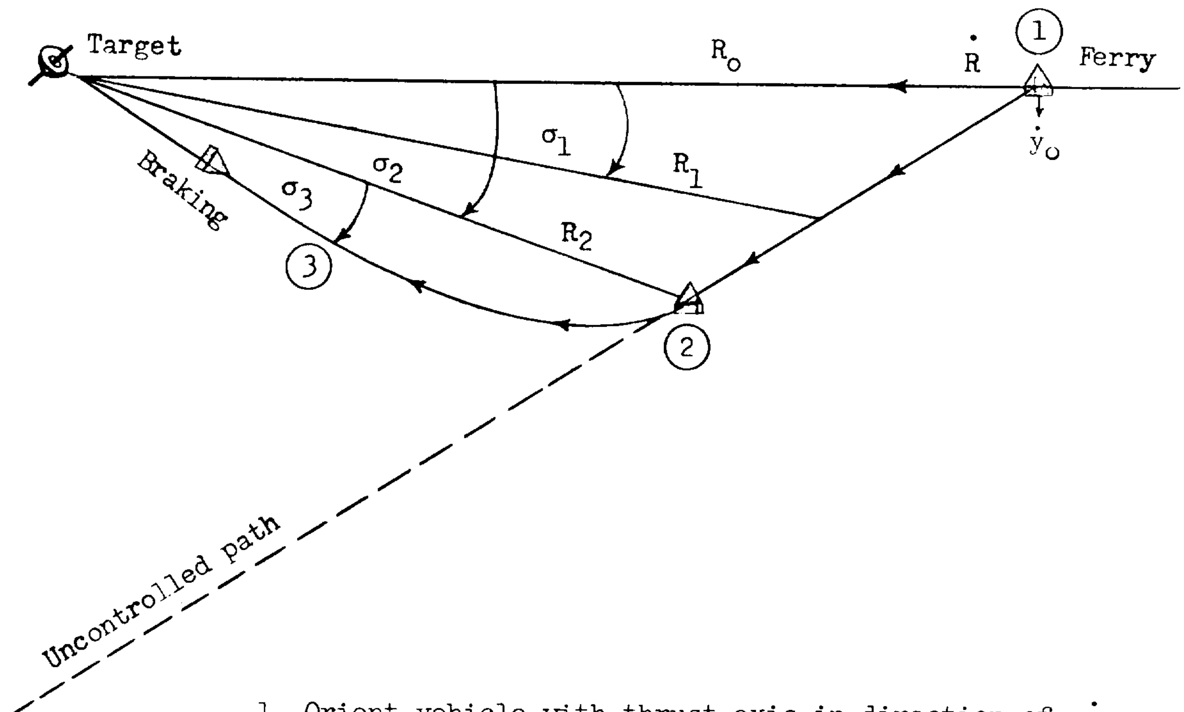

1. Orient vehicle with thrust axis in direction of $\dot{y}_o$
2. Measure σ_1, t_1 and σ_2, t_2
3. Thrust to zero angular velocity and measure σ_3, t_3

   then $R_2\sigma_3 = \dfrac{at_3^{\,2}}{2}$ or $R_2 = \dfrac{at_3^{\,2}}{2\sigma_3}$

4. Using $R \sin \sigma = \dot{y}_o t$,

   $R_1\sigma_1 = \dot{y}_o t_1$ and $R_2\sigma_2 = \dot{y}_o t_2$

   thus $\dfrac{R_1}{R_2} = \dfrac{\sigma_2 t_1}{\sigma_1 t_2}$, or $R_1 = \dfrac{\sigma_2 t_1}{\sigma_1 t_2} R_2$

5. Then $\dot{R} = \dfrac{R_2 - R_1}{t_2 - t_1}$

Figure 4.- Description of one technique for determining relative range and closure rate between two space vehicles.

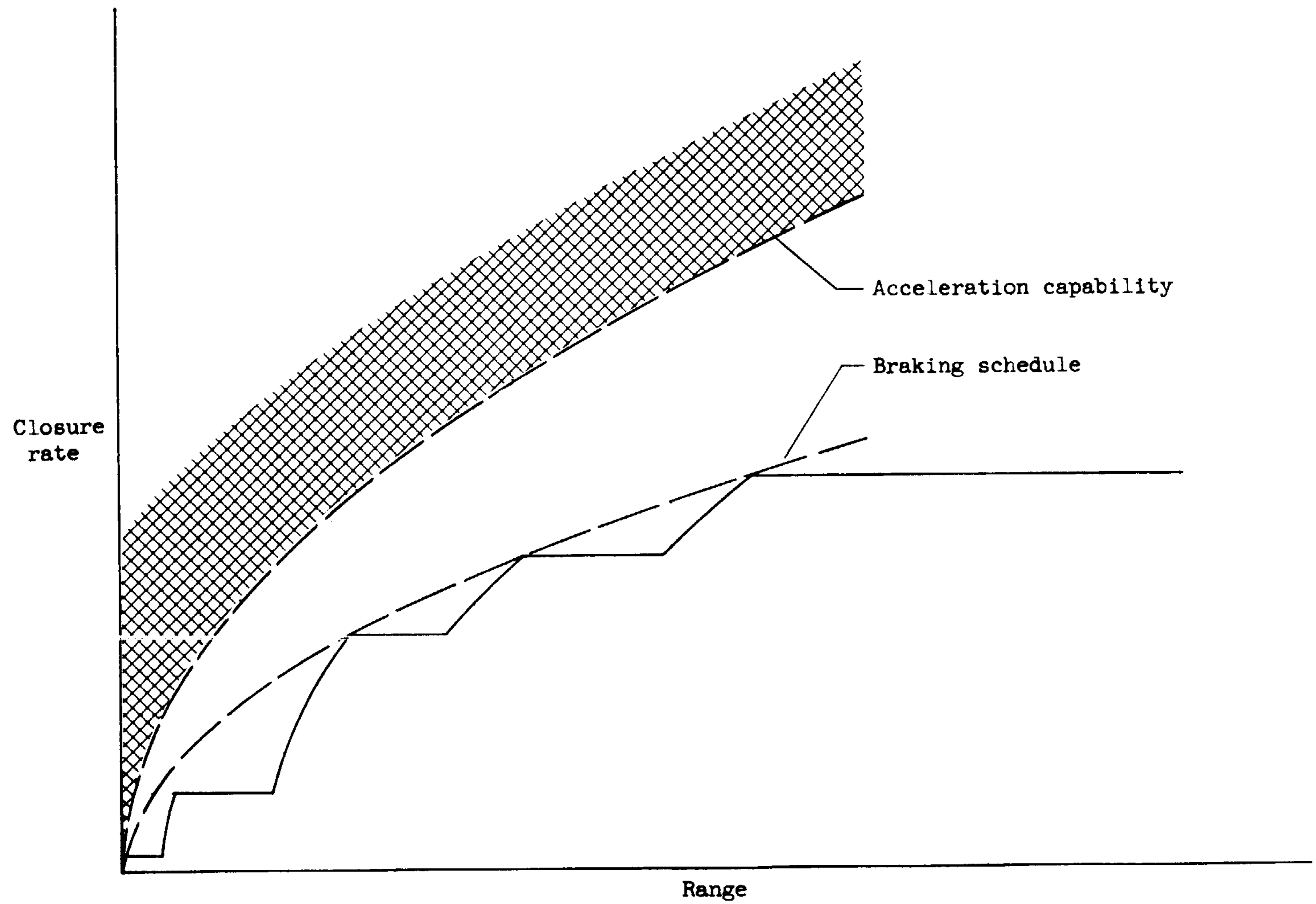

Figure 5.- Arbitrary braking schedule related to acceleration capability of vehicle being controlled.

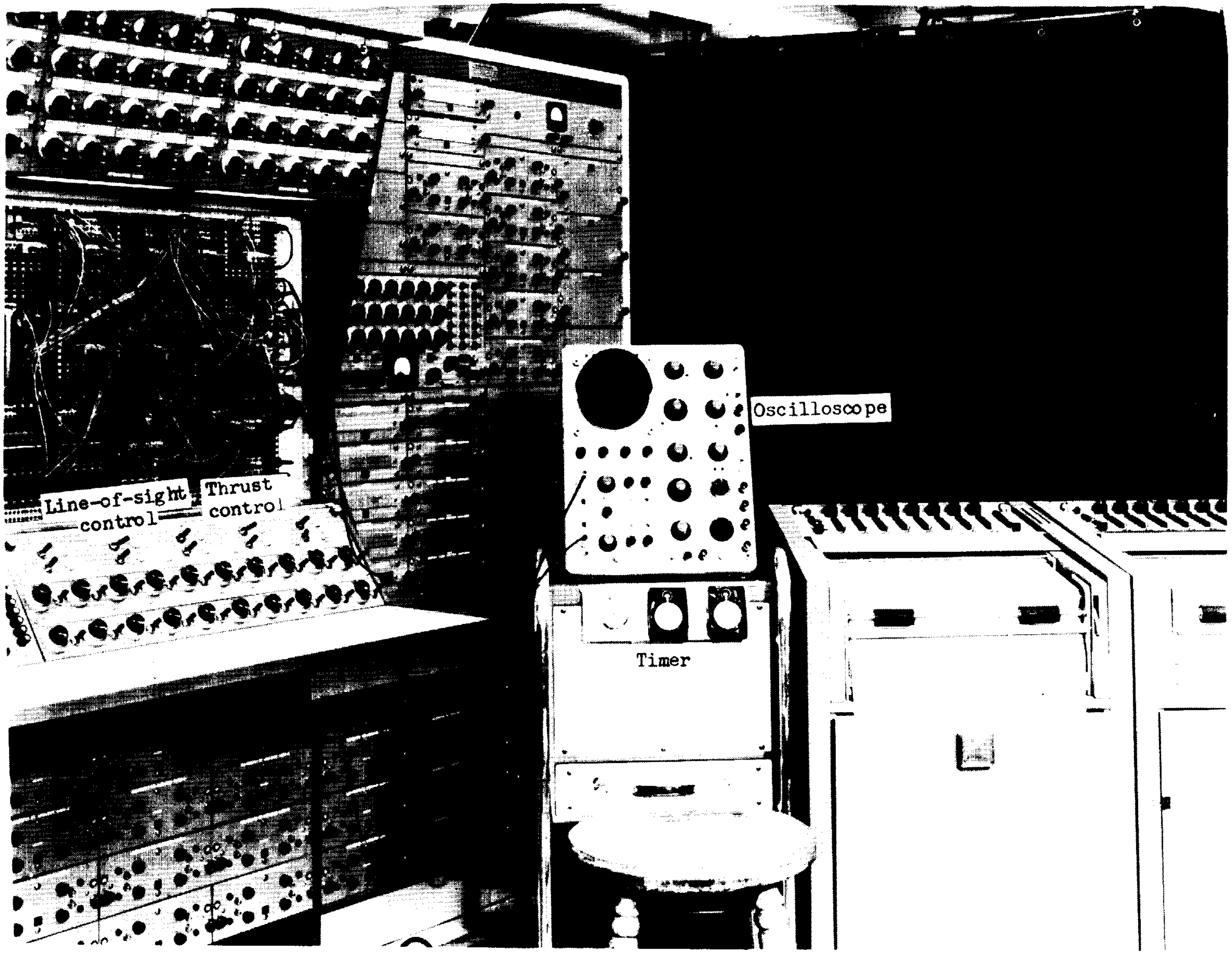

Figure 6.- Photograph of simulation equipment. L-61-1611

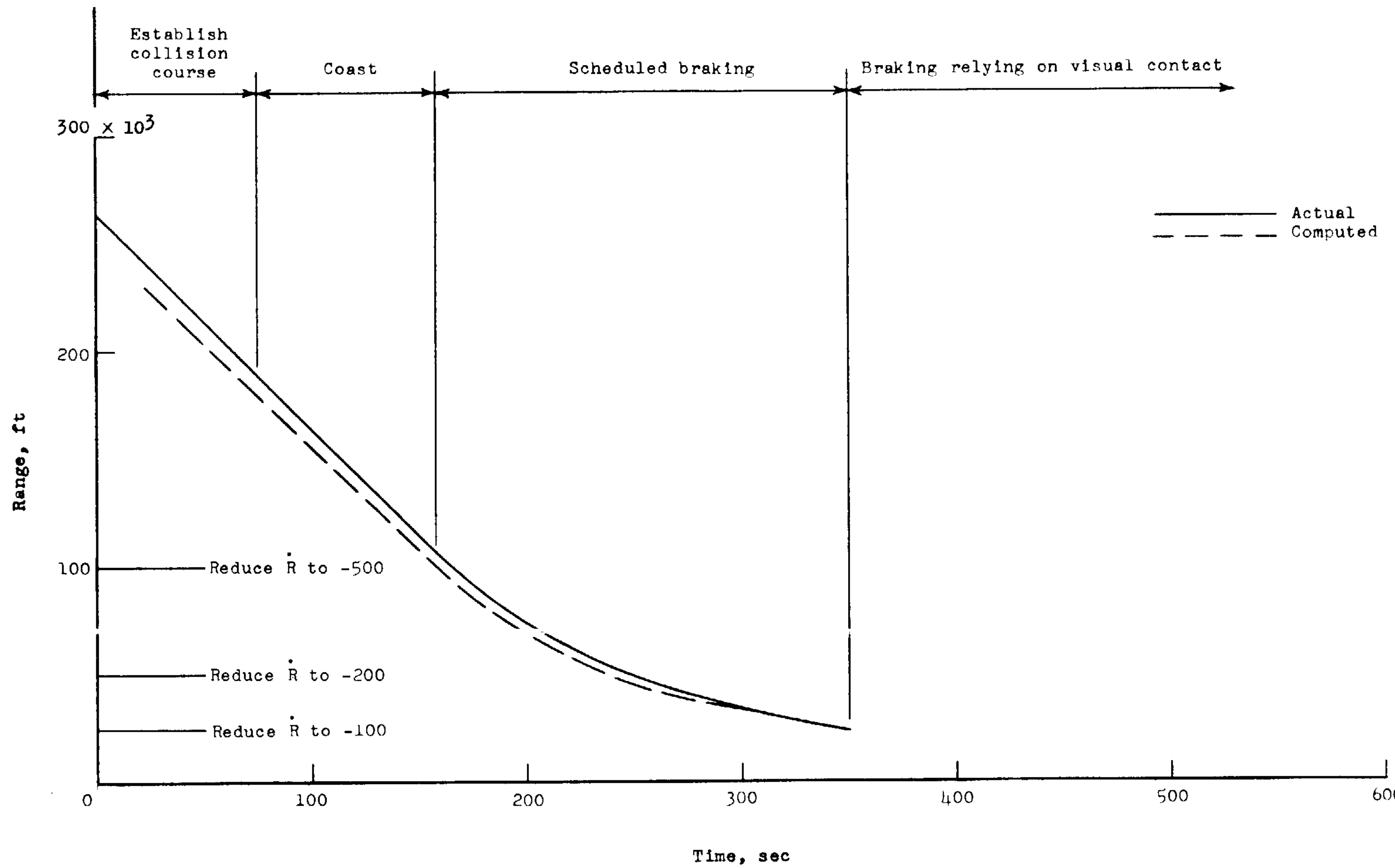

Figure 7.- Time history of a rendezvous maneuver performed with the technique evaluated in table I. (Run no. 6)

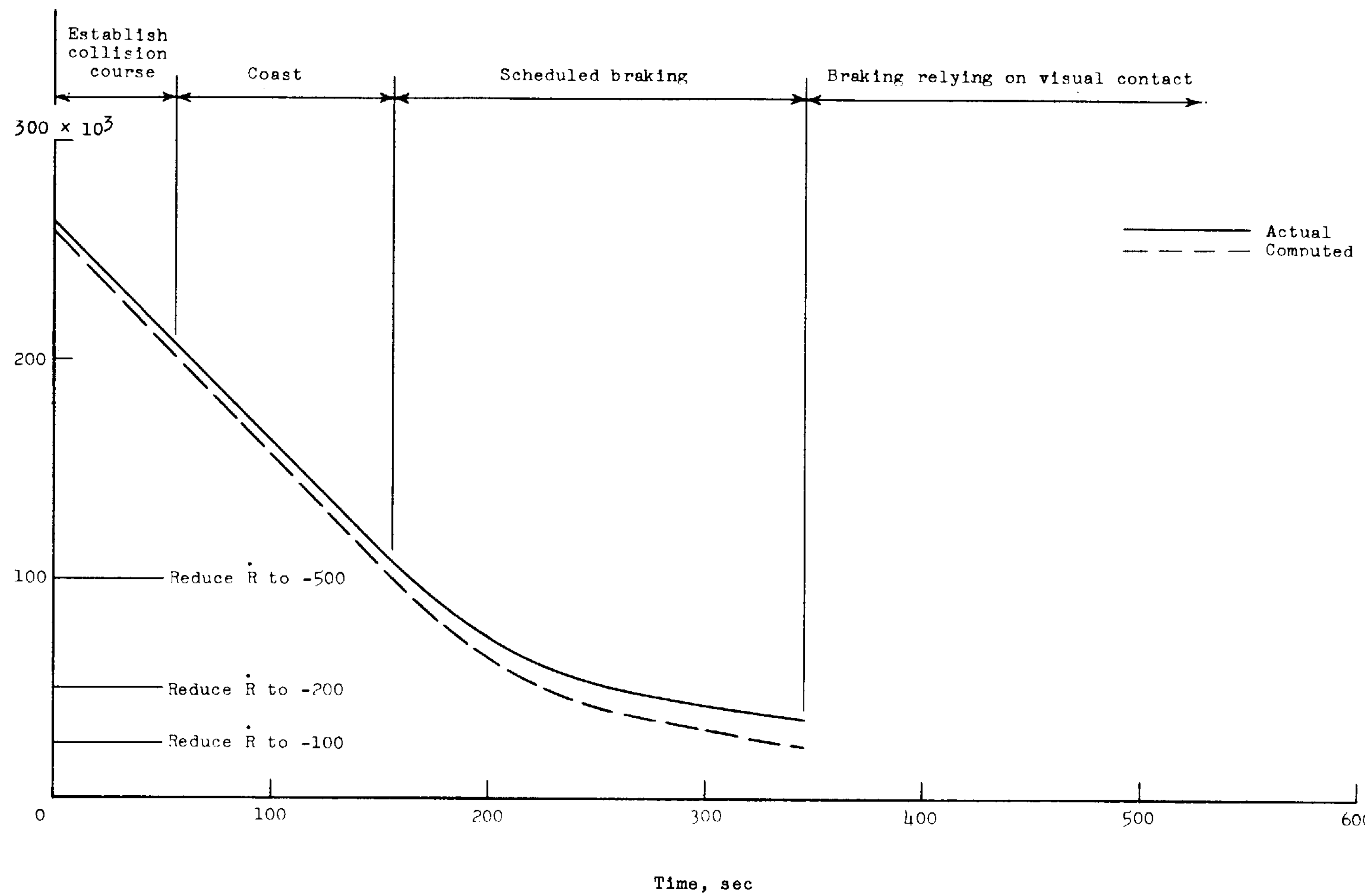

Figure 8.- Time history of a rendezvous maneuver performed with the technique evaluated in table II. (Run no. 4)

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